DEVELOPING HIGH ARCH DAMS – A COMPREHENSIVE EXPERIENCE

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Abstract: The planning and construction of large dams are very intricate and complex tasks. Coordination of studies and planning of work phases require a highly competent task force. A team of experienced engineers with a broad spectrum of competences is a key success factor. They must be backed up by top specialists and experts for specific studies; contracts specialists prove very useful too.

Due to their long life time span, these complex projects do not evolve linearly; they require constant adjustments and repositioning, depending on the events occurring during their development. Moreover, as important safety issues are at stake, the dilemma of the profitability of a project and the rapidity of its implementation vs. the work quality and the adequacy of the methods relied on becomes oftentimes of critical importance.

The issue of the type of contract to adopt between the parties involved in a project also often proves crucial. All these reflections are illustrated by examples drawn from five high arch dam projects STUCKY SA worked on these past ten years. The following issues are addressed :

Dam	Height	Specific issues addressed
Bakhtyari arch dam, Iran	315 m	Basic and preliminary studies
Luzzone arch dam, Switzerland	225 m	Heightening of an existing large dam
Deriner arch dam, Turkey	253 m	Interactions between design and implementation
Karun IV arch dam, Iran	230 m	Role of an Advisor by a Contractor
Enguri arch dam, Georgia	272 m	Rehabilitation of a high arch dam

The importance of the proper timing of key decisions and fundamental choices is stressed, as well as the requirements set on the initial design and implementation of a dam for facilitating future interventions on the structure. New and promising perspectives for the construction of arch dams are finally briefly presented.

Key words: High arch dam, design, heightening, rehabilitation, implementation

1 Introduction

Since immemorial times, dams have been built to meet the need of providing water for human activities. Evolving from simple structures erected tens of centuries ago, they gradually gained in boldness and complexity. Their height constantly increased, as the volume of water retained behind the walls. Gradually, the insight in their internal function got refined, passing from a mere instinctive and qualitative comprehension to a more formal and quantitative description of the forces they are submitted to. In a sense, this evolution reflects a general progression of the human genius, from which they are a concrete expression, and also a concretization of the faith in an idea.

Among all the types of dams that have been built, the arch dams occupy a special position. More than a simple stack of material destined to bar a valley, their shape reflects the intimate knowledge of the various interactions between the structure and its environment. The extreme sobriety of their constituents and the apparent simplicity of their shape only partly reflects the ingenuity of their conception. Their essential forms, allying aesthetics and formal rigour, materially underline the essence of their function, which is to control the huge forces caused by the retained water.

Even more striking are the challenges set by the very high arch dams (higher than 200 m). The immense forces caused by the water pressure in the reservoir have to be captured and mastered by a thin wall; the positioning of such a high structure in a valley has to outsmart the traps set by the nature, in particular the geology; the logistics of the construction site must be designed for a very large endeavour. All these constraints combine together to make the problem even more complex.

The particularly long duration of the project, from the first sketches to the dam commissioning, also imposes to carefully plan the continuity of the key staff involved. But the result of so many efforts can be breathtaking: the perfection of a high arch dam shape erases the size of the wall, despite its imposing height. Of course, the various risks and the financial load linked to these extreme structures are particularly high, as only heavy investments allow such large works, which in turn create in general huge water volumes, with all the subsequent risks.

It is important for an engineering company active in dam projects to strive to constantly remain involved in the different phases of large dam projects: conception, design, realization, rehabilitation. This allows to keep the competences of the key staff at a high level and to guarantee the progression of their knowledge in tune with the latest technological and conceptual developments. The reflections presented below have been gathered during the involvement in several very high arch dams projects, all realized within the past decade. The lessons learnt from these real cases are therefore all but outdated; they shall contribute to give a broad and actual overview of the main challenges facing the Designers and Constructors of such projects.

2 Preliminary studies: Bakhtyari arch dam (Iran, 315 m)

At the onset of any dam project, especially for the large and very large ones, a number of exploratory and preliminary studies have to be carried out. This step is critical for the success of the project, as it conditions the whole progress of the subsequent works – and consequently its cost. It is however a widespread temptation by project sponsors to look twice on the expenses devoted to these studies, and to rather channel them into "productive" conceptual activities.

Before this can be done however, the best solution has to be found, out of tens of possible options and hundreds of thinkable combinations. The initial coordination of all components of a complex project, the determination of their key relationships, the qualitative and quantitative characterization of their influences, the validation of their compatibility are all fundamental to the successful development of the project. In addition, a number of reconnaissance campaigns and specific studies have to be carried out in particular fields, such as geology, geotechnics, hydrology, seismicity.

In this early project phase, the Engineer usually works for the future Owner of the structure. For very large dam projects, the execution all these activities and the integration of their findings and conclusions require a highly competent team, composed of top specialists as well as experienced all-rounders. Among other qualities, these professionals have to be quite dependable in their work, yet remain highly flexible and cooperative in their individual approach, to ensure a smooth coordination of all fields and the best possible common integration of the various pieces of the big puzzle. The correct balance between the specialists in charge of these partly conflicting, partly complementary requirements, is one of the keys to the successful launch of complex projects.

The capacity to ensure a broad thinking approach, integrating extremely diverse elements, to rapidly foresee consequences in a field of decisions taken in another field, are of paramount importance at this stage of a complex project. It is indeed highly important to orient very early the fundamental decisions into the right direction, allowing then to only adjust and fine-tune the selected concept as the project develops. A sub-optimal set of decisions resulting from unripe conclusions or insufficient investment in initial studies may lead to major subsequent re-orientations of the project, with higher costs at last. As adaptations would anyway have to be brought to the initial concept, it is of highest importance to make sure that the magnitude and consequences of these changes are under control right from the beginning of the studies.

The capacity of rapidly providing reliable raw data and orders of magnitude – even though they might be approximate in a first shot – also allows a rapid progress of the initial studies. The data collection can then be reoriented if necessary, as a consequence of first reflections based on the succinct initial set of information. The second step of data gathering shall then be shaped to guarantee completeness, appropriateness and reliability of the available information, and ensure that the deductions and conclusions based on these data will allow an optimal definition of the project and its components.

As an example of the critical importance of preliminary studies, it is worth mentioning the case of the Bakhtyari dam & HPP project (Iran). The dam is planned to become the highest arch dam in the world (315 m); it will be located in a difficult topography, with steep slopes in a narrow valley. Due to the very limited room available, almost all construction facilities will be located in the gorge downstream of the dam. As, due to the huge structure size, the construction will extend over a decade or so, the correct design of the diversion system is a key factor to guarantee the uninterrupted progress of the dam erection, specially during the rainy season.

The figure 1 presents the statistics of the annual peak flow observed from 1967-68 to 2004-05 in the Bakhtyari river nearby the dam site. One notices that during the 11 last recorded years, no less than three large floods were observed, whereas during the 27 preceding years, such a magnitude was never recorded. Why this sudden concentration of large floods? Is it a pure coincidence? A sign of climate change? How shall this be interpreted? Can this give a clue about the evolution of the annual peak flow during the construction period?

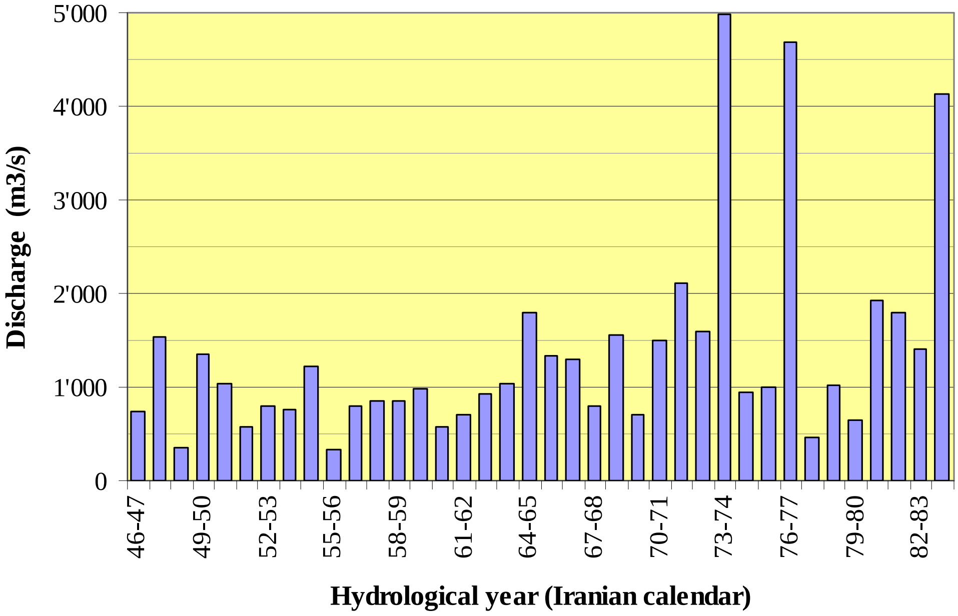

Figure 1. Annual peak flows recorded nearby Bakhtyari dam site

In autumn 2005, the decision was made to consider this phenomenon as a serious potential threat for the construction site and to double the diversion system sketched a few years earlier. The second diversion gallery was integrated into the overall construction system to facilitate the access to the upstream side of the dam. The decision revealed amply judicious: in February 2006, a fourth large flood hit the dam site. It is now expected that more will occur in the coming years.

3 Heightening of an existing dam: Luzzone arch dam (Switzerland, 225 m)

Some technical conditions are required for a heightening of an existing dam. Among them, some important are:

Ÿ Behaviour of the existing dam well known and without any abnormality;
Ÿ Quality of the existing concrete sufficient to resist the increase of stresses;
Ÿ Uplift pressure distribution well known and its increase due to heightening considered;
Ÿ Behaviour of the foundation well known and without any abnormality; capacity to resist against the increased forces;
Ÿ Topography able to transfer the forces of the heightened part;
Ÿ Watertightness of the extended reservoir garanteed without any risk of land sliding.

Apart from the above technical issues, the effect of construction works on the reservoir operation and energy production as well as logistics – access road, installation of the new construction site, etc. – could play an important role in the making of decision. Beside safety issues, one of the highest priorities of the dam Owner is a guaranteed operation throughout the construction period, which is an major constraint for a heightening project in a narrow valley. Indeed, most projects of this type are very challenging.

In the 90s, there were two important heightening projects in Switzerland: Mauvoisin arch dam in 1991 and Luzzone arch dam in 1998. Being the second highest arch dam in Switzerland, constructed in 1963, Luzzone dam is situated in the southern slope of the Swiss Alps.

Switzerland has developed 85% of its economically feasible hydroelectrical potential [1]. Most artificial reservoirs are filled during the summer, whereas the high electricity demand is in winter. In addition, the value of hydropower energy increases in Europe, for peak energy and network regulation. Therefore, large reservoirs capable to store the summer water resources and allow electricity production during winter to meet daily peak demand are key assets of energy producers.

Due to various environmental and topographical constraints, the best option in Switzerland would be to optimise, renovate and increase the capacity of the existing schemes. Heightening of Luzzone arch dam was a successful project in this respect, in which a 17 m heightening of the dam (8%) allowed to increase by 23% the total reservoir volume (see figure 2).

Most of such projects are real challenges from the technical and logistical points of view. The heightening of Luzzone arch dam, despite satisfying most of the required conditions for a successful heightening, had to be carried out under the following constraints:

- The dam crest serves as a main access road to the left bank of the valley;
- The topography of the left abutment is unfavourable.

Figure 2. Construction site of heightening of Luzzone dam – The work progress is clearly visible, as the unusual solution found to replace the left abutment

All these technical obstacles had been considered to carry out the heightening of the dam. Since the heightening was designed as an extension of the dam geometry, the road was maintained in the same position; a tunnel was integrated into the heightened part.

On the left abutment, the topographical conditions are not favourable and do not allow an appropriate abutment for the new arches. This particularity was at the origin of a rather unusual and bold design, quite challenging in terms of thrust flow analysis. The new arches are cut close to the left abutment and the radial joints partially or not grouted for the highest blocks on the left bank. The arch action is progressively bent down, eliminating the need of a strong left abutment on the crest elevation. Static and dynamic analyses of the heightened dam concluded that the safety of the heightened dam is satisfactory.

Additionally, the grout curtain was adapted to the new conditions and drainage galleries of the left bank were improved. Some minor modifications were also needed to adapt the spillway to the heightened reservoir conditions. Since its heightening, the dam is under regular inspection and monitoring and has shown a satisfactory behaviour.

4 Interactions of design and implementation: Deriner arch dam (Turkey, 253 m)

It is not unusual that the Engineer directly works for the Contractor in charge of an arch dam construction. The tasks of the Engineer are then twofold and sometimes difficult to reconcile:

- On one hand the Engineer must perform the Construction Design, on which the final drawings are prepared and the arch dam is built. This stage must encompass all geological, seismic and hydrological data gathered earlier, to reflect as fully as possible the natural conditions. This sets constraints and forces to the structures and determines their optimal shape and functioning. This stage can be seen as the last theoretical step of the project.
- On the other hand, the Engineer is expected to advise the Contractor on site on many practical and technical issues. In many occasions the conditions faced on site turn out to be different from the assumptions made earlier and as such, incompatible with the design. It is not the least difficulty for the Engineer to adapt the design to the effective conditions; this can only happen harmoniously with a comprehensive and global approach of the problems.

A strong theoretical background regarding all design specificities and a deep sensitivity to the practical aspects of the construction are thus required simultaneously. In addition, the long time span of such high arch dam projects also requires the continuity of the engineering team; this is often best provided by combining young engineers with more seasoned expert engineers.

The example of Deriner arch dam & HPP project is relevant in this respect. This high arch dam (253 m) is currently under construction in north-eastern Turkey on the Çoruh River. Once completed, this hydroelectric scheme will provide 670 MW.

The team involved in the final design of the dam during the Construction Design stage was a blend of young designers at the cutting edge of the latest theoretical developments, and more experienced dam experts gathering several decades of arch dam design. The same team is currently on site, following the construction and advising the Contractor. Such a continuity allows the younger engineers to be confronted to the site contingencies and to adapt if necessary the dam design to the local conditions without compromising on the key elements of the structure. Thanks to this continuity, the design can be improved within an optimal coordination framework and high level engineering services are being delivered to the Contractor and dam Owner.

A direct example of such synergy between design work and practical site follow-up occurred for the dam foundation excavation, which requested in many sections the implementation of heavy supporting means like prestressed anchors. Thanks to a valuable design job conducted along with a sensitivity analysis covering many variables (characteristics of rock mass and geotechnical values, slope and height of excavation, types of support, etc.) and the development of a versatile software tool that could easily handle any excavation layout, it was possible to propose on the spot tailor-made solutions during all the excavation phase, allowing to optimise the safety and cost of the dam footprint excavation.

Such an accountable approach also allows the transfer of knowledge within the Company, from the most experienced to the next dam designer generation. Passing the knowledge (be it theoretical or practical) from one generation to the next is key to guarantee the long-term perenniality of an engineering team; this is by far best realised by working together and sharing the daily activities and contingencies during the many years of the project design and construction lifecycle. In Deriner, the first concreting steps are a result of this coordinated philosophy (see figure 3).

Figure 3. Deriner arch dam (Turkey), 253 m high, under construction

5 Construction works: Karun IV arch dam (Iran, 230 m)

The success of the implementation of a complex structure – a high arch dam, e.g. – depends to a large extent on the intelligent and efficient organization of the construction site. All the conceptual issues being solved in earlier planning stages, the project faces the hard reality challenge, as the problems that will have to be solved during this phase are almost exclusively of practical nature.

The mastering of the interactions between structures and logistics becomes a key factor of the successful completion of the scheme. The visionary and theoretical approaches prevailing in the earlier stages have to give way to technique and organization. One of the first consequences being the verification of the hypotheses made at the design stage (in particular about the geological and geotechnical features, readily validated during the excavation works). The rightness of the assumptions made for the design of the diversion system (cofferdams, diversion gallery) similarly undergoes a sharp test through the floods that inevitably occur during the construction time.

All usual problems encountered on a construction site are magnified by the size of the structure to erect: very large material volumes (excavation material to evacuate, concrete to bring in), very large heights (pump pressure, cable weight, transport time), very long construction time (resistance of equipment, increased probability of large flood) are only a few of the difficulties specific to this kind of structures.

The Engineer often works as an Advisor to a Contractor or as a Supervisor for the Owner during the construction stage. His skills in organizational matters and the practical resolution of the problems set by the design are crucial to the smooth progress of the construction. Among his tasks, he will have to try to industrialize as much as possible the repeated activities, in order to save time, secure the work quality or simply guarantee the punctual completion of the works.

A good technical knowledge and an excellent field experience are necessary requirements for such a position. A sharp sense of anticipation and a flair for improvisation too, as the reality usually tends to escape rigid schemes and always tries to take its own way. His role of local relay between the Designer, the Contractor, the Owner and the Manufacturers entrusts the Engineer a key importance. He will be set in a dichotomous position, since he has to work "hands-on" to solve local problems, while simultaneously stay at a distance to keep an overview of the construction site.

As an example of key decisions to prepare is the case of the Karun IV hydropower scheme (Iran). The dam itself will be a large arch dam (230 m), which has been designed on the basis of geological and topographical criteria, without consideration to the construction process. The whole chain of concrete preparation and placing had to be developed in a challenging topographical setting.

In particular, the pre-cooling of the aggregates, whose temperature can easily reach 50°C in summer, was critical in terms of concrete quality and energy consumption. A two-step process has been developed, with a first, "natural" cooling from 50° to 35° with river water, followed by a second, "forced" cooling with 4° cold water; this second step brings the temperature down from 35° to 24°. The water for the mixing of the aggregates and cement is finally replaced by ice, bringing the temperature of the final mixture down to some 18°C. The two-step process takes more time than an usual one-step cooling but, considering the large volume of the structure, saves enormous amounts of energy.

Another value-added set of activities brought by the Advisor was the negotiation and purchase of construction equipment with foreign suppliers. Difficulties were easily prevented by appealing to him, whose personal relation network and cultural proximity with the suppliers could ensure favourable contracts and a rapid delivery. The installation of the equipment was also significantly eased thanks to his intervention.

6 Rehabilitation of an existing dam: Inguri arch dam (Georgia, 272 m)

For several decades the main challenge about dams (and arch dams) was to build them as safely and economically as possible, and also as rapidly as possible to meet the increasing power demand. A trend developed in the last years is expected to become more acute in the 21st century: the new challenge will be to maintain and rehabilitate the dams.

This task proves to be much more intricate and difficult to handle than the mere construction of a new structure. Indeed when the needs are felt to rehabilitate the dam or parts of it, usually the damage to the structure is already too extensive to be fixed with light means. In addition, the dam Owner is usually reluctant to cut the power generation, which would reflect in direct operating losses adding to the rehabilitation costs. Therefore the rehabilitation works should be carried out as much as possible without interferring on the operation. The job site logistics is much more tricky to organise, but oftentimes requires operational compromises (reduced maximal water level, e.g.).

Eventually, the job is sometimes difficult because of the lack of reliable information, data, and knowledge from the construction time. Namely only rarely is the dam Owner able to provide original documents, design notes, construction or as-built drawings of the structures, and therefore either conservative assumptions have to be made by the Engineer in charge of the rehabilitation, which in turn will result in high costs, or expensive and time-consuming exploratory test programs (on rock and concrete samples, for instance) have to be carried out (when possible) to ascertain more accurately the site conditions of the dam and its surrounding foundations.

Such difficult conditions were faced in the past decade in the rehabilitation works of the Enguri dam and HPP in Georgia,which is no less than the tallest arch dam in the world (see figure 4).

Figure 4. Enguri Arch Dam in Georgia, 271.5 m high

This scheme was constructed in the 70s and 80s, and has been put into operation since 1978 at a reduced head. In the 90s for economic reasons and especially due to the civil unrest in the region, the structures have suffered from neglect and lack of maintenance. Since 1995, the scheme has been found with several defects [2], amongst which the most critical regarding the dam were :

- the status of the monitoring equipment, damaged, unreliable and/or out of order;
- the drainage system acting too efficiently, thus presenting a risk of internal erosion that eventually could be a potential concern for the dam foundations;
- the grout curtain locally in poor conditions.

Several rehabilitation works were recently carried out to rehabilitate the arch dam, and still more are to be undertaken. Those works require highly specific capacities. Much new information is unearthed during the process and an innovative and proactive Engineer is to be sourced, capable of adapting quickly the rehabilitation philosophy to the practical work within the allocated budget. The ability to prioritise the most urgent remedial works, or the capacity to revise the project in real time and in accordance with the latest technical data or time and budget constraints are only two of the many qualities that were requested to conduct the Enguri dam rehabilitation project.

Not to neglect in such context is the flexibility and cooperation required from the Contractor. This is paramount when selecting which Contractor should be allocated the works.

The need to keep detailed construction and as-built documents, as well as operation records was emphasised. The availability of such reliable documents can greatly help the rehabilitation project to be designed and planned in the most efficient and optimal way. A new data base had to be started, gathering and filing the documents, and exploiting as much as possible the recovered information. This data base should also help improve the design of future rehabilitation works.

Eventually concerning the contractual and financing aspects, it was found necessary to identify flexible procurement and financial arrangements to allow the risks for the Owner and the Contractor to be mitigated and absorb the many changes that occurred during the execution of the rehabilitation project in terms of cost and schedule.

7 Conclusion

The capacity to master the whole life of a high arch dam project – from first studies to dam commissioning – is a highly valuable asset for an Engineer. The complex interactions between structures, spatial / temporal imbrication of activities and natural constraints may lead to high over-costs if not properly dealt with. Only a broad base approach can offer guarantees that the project is well balanced, thus resulting in a high work quality and optimal costs.

All in all, the very high arch dams require an unusual blend of competences and talents to be optimally designed and efficiently implemented. The mere accumulation of peak individual technical and organisational competences does not guarantee success. The project team must also include experienced all-rounders, able to fill up the gaps between the individual competences.

Almost all the design and supervision tasks can indeed be successfully accomplished by most experienced engineers. Some intricate studies and activities however require an additional amount of expertise, which the Developer of a project should not hesitate to rely upon. The incurred costs of this additional expertise are in general largely repaid by the added value brought to the project, the subsequent savings or the rapid solution proposed to potentially critical problems.

To secure the chances of success in the design and implementation of a high arch dam project, its Developer should consider two key aspects in the choice of the Engineer :

- to rely on an experienced team, well tuned and flexible, composed of top specialists as well as highly experienced all-rounders;
- to ensure that the experience portfolio of this team covers all aspects of the life of such a project, and this in a past as recent as possible.

This is indeed only one aspect of all the components to integrate during the decade or so a project will cover from its first concept to its commissioning.

The involvement during the past years in several very high, thus demanding, arch dams projects allowed to gain substantial additional experience within the Company, and – interesting and valuable side effect – the design creativity has been fostered. Promising innovations are uncovered in the field of the design and construction of arch dams, such as the STOD construction method, applying Roller Compacted Concrete (RCC) to the construction of double curvature arch dams [3], or other in-house specific design tools developed and improved in the framework of the projects described in this paper. They all are now part of the knowledge of STUCKY and are integrated into the internal design and construction processes.

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